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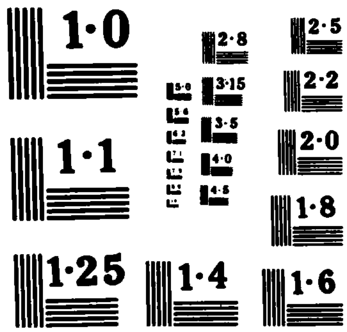

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Operational Window for a Plasma Erosion Opening Switch Used for Voltage Multiplication on Pulsed Power Generators

P. F. OTTINGER

Plasma Technology Branch
Plasma Physics Division

June 5, 1985

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The Plasma Erosion Opening Switch (PEOS) is a fast opening switch which has been shown to be capable of conducting megampere-level currents before opening in <10 ns. Such a switch can be used for inductive storage in order to compress the output from conventional pulsed power generator in order to achieve voltage and power multiplication. An operational window is described herein which illustrates the voltage regime made accessible for a given machine by the switch.

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OPERATIONAL WINDOW FOR A PLASMA EROSION OPENING SWITCH USED FOR VOLTAGE MULTIPLICATION ON PULSED POWER GENERATORS

The Plasma Erosion Opening Switch (PEOS) is a fast opening switch which has been shown to be capable of conducting megampere-level currents before opening in < 10 ns.[1] Such a switch can be used for inductive storage in order to compress the output from conventional pulsed power generator in order to achieve voltage and power multiplication.[2-7] An operational window is described herein which illustrates the voltage regime made accessible for a given machine by the switch.

The physics understanding of how the PEOS conducts current and then opens is presented elsewhere[8] and will not be described in detail here. Of importance here is only that when the switch opens a gap is opened by erosion at the cathode surface in the switch region and that the switch opening process is complete when the electron flow off the cathode in this switch region becomes magnetically insulated (see Fig. 1). For a machine configured in cylindrical geometry such as Gamble I shown in Figure 2(a), this insulating magnetic field depends inversely on the cathode radius, R_c. For a triplate disk feed such as on PBFA I the insulating magnetic field depends inversely on the distance of the switch region from the center line of the machine also labeled by R_c in Fig. 2(b).

In order to get a feeling for the operational window for switching using a PEOS, consider the following. Good switching action requires that the load current exceed the critical current for magnetic insulation of the electron flow in the switch region. Thus

$$I_\ell(A) > (1.6)\,(8500\ \beta\ \gamma\ R_c/D), \tag{1}$$

where I_ℓ is the load current, 1.6 is a geometry factor determined by PIC code

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runs,[9] $\beta = (1 - 1/\gamma^2)^{1/2}$, $\gamma = 1 + V(MV)/0.511$, V is the voltage across the switch, R_c is the radius of the cathode in the switch region and D is the switch vacuum gap at the time of insulation. For a load impedance of Z_ℓ, the load current is approximately $I_\ell \sim V/Z_\ell$. Solving Eq. (1) for V yields

$$V > \frac{(0.026\ Z_\ell R_c/D)^2}{1 - (0.026\ Z_\ell R_c/D)^2}. \qquad (2)$$

In other words, for a given load impedance the voltage must be high enough to provide sufficient load current for insulation.

On the other hand, a given machine can only supply a limited amount of current. During the conduction phase the switch acts as a short circuit allowing the storage inductor, L, shown in Fig. 3 to be current charged to at most $I = f\ V_{oc}^p/Z_g$. Here V_{oc}^p is the peak open circuit voltage of the generator, Z_g is its characteristic impedance and $f(\tau_p L)$ is a factor which is ≤ 1 and depends on the open circuit voltage waveform (represented by its dependence on the pulse duration, τ_p and on L. The factor f can be associated with the efficiency of transferring energy out of the machine into the inductor. The current which is switched by the PEOS from the storage inductor, L, to the load, Z_ℓ, is less than this by at least a factor $\exp(-Z_\ell \Delta\tau/L)$ where $\Delta\tau$ is related to the switching time and it is assumed that the inductance, L', between the switch and the load is negligible compared with L. This factor represents the resistive decay of the current during the switching time. Combining these factors results in a load current, $I_\ell = (f\ V_{oc}^p/Z_g) \exp(-Z_\ell \Delta t/L)$. Defining Δt still remains.

If time $t = 0$ is defined to be the time at which the switch begins to open and drive current through the load, and if $t = t_s$ is defined to be the time of peak load current, then the risetime of the load current, t_s, can be

defined as the switching time. Using this definition Δt and t_s can be related through

$$Z_\ell \Delta t \equiv \int_0^{t_s} \left(\frac{Z_\ell Z_s}{Z_\ell + Z_s} \right) dt.$$

Here Z_s is the switch impedance and the integral represents the parallel impedance of the switch and the load averaged over the switching time. If Z_s rises rapidly to a value $\gg Z_\ell$ by $t = t_s$, then $\Delta t \approx t_s$, but in general $\Delta t < t_s$. Here it will be assumed that Z_s does rise rapidly so that $\Delta t \sim t_s$.

Keeping in mind the relationship of Δt and t_s then $V = Z_\ell I_\ell$ is limited by

$$V \leq \left(Z_\ell f V^P_{oc} / Z_g \right) \exp\left(- Z_\ell \Delta t / L \right). \tag{3}$$

This is clearly an upper limit, but for the sake of finding the operational window this value will be used. If, for example, there is a current loss in the region between the switch and the load, then the load voltage will be less than that given in Eq. (3). This could happen if significant vacuum electron flow off the cathode in the switch region reaches the anode surface before entering the load region.

The open circuit voltage waveforms for various generators are shown in Fig. 4. Using these input voltage waveforms in the circuit shown in Fig. 3 with $Z_s = 0$, the maximum energy (i.e., $LI^2/2$) transferred to the inductor L can be computed. This energy, $E_L(\tau_p, L)$, is plotted as a function of L in Fig. 5 for various generators.[10-11] The peaks in the curves represent the best matched inductance for energy transfer from the generators, however, the peaks are relatively broad. The factor $f(\tau_p, L)$ in Eq. (3) can be obtained from Fig. 5 through

$$f = \frac{Z_g}{V_{oc}^P}\left(\frac{2E_L(\tau_p, L)}{L}\right). \tag{4}$$

Thus for a given L and Δt Eq. (3) can be used to specify the maximum load voltage as a function Z_ℓ for each generator.

The operational window for a PEOS on a specified pulsed power generator is defined by Eqs. (2) and (3). As an example, consider the results for Gamble I with Δt = 10 ns shown in Fig. 6. The dashed line is a plot of Eq. (3) and indicates the maximum load voltage Gamble I can expect to drive on a load of impedance Z_ℓ with a storage inductance of 100 nH and with an opening switch that opens in ~ 10 ns. Voltages above this line are not accessible. The curve peaks and begins to fall off when the L/R decay time of the current becomes comparable with or longer than the opening time Δt of the switch. If the switch opens faster (i.e., Δt is decreased), this dashed curve will move up and higher voltages are accessible. On most of the plots that follow dashed curves for three inductances are shown, one for the value of L^{max} which couples the most energy into the inductor from the generator, one for L somewhat smaller than this L^{max} and one for L somewhat larger than this L^{max}.

The solid curves in Fig. 6 are plots of Eq. (2) for R_C/D = 3, 5 and 10. Below and to the right of one of these curves for a given R_C/D the electron flow in the switch region is not fully insulated and therefore the switch will not completely open. Above and to the left of this solid curve the flow is insulated and the switch will open completely. If the switch gap, D, is larger the switch can hold off more voltage while still remaining open. This results in the solid curve moving to the right. The shaded region between the solid and dashed curves in Fig. 6 then represents the operational window for the switch with R_C/D = 3 and L = 100 nH. The plots that follow will contain a

number of solid curves over a range of values of R_c/D.

Figure 7 shows the same plot for Gamble I as in Fig. 6 but with Δt = 5 ns. The dashed curve moves up because less energy is dissipated during switching. This illustrates how higher voltage is accessible with a faster opening switch. Figures 8, 9, 10 and 11 show the same results with Δt = 10 ns for Gamble II, Supermite, PBFA I and PBFA II respectively. Similarly, Figures 12, 13, 14 and 15 show results with Δt = 5 ns for the same generators.

The results presented here scope out the regime where the PEOS operates well when positioned with a cathode radius R_c on a given generator with a storage inductance L. For a specified gap, D, and opening time, Δt, these plots show what voltage is accessible and what load impedance is necessary to obtain it. If a higher load impedance is used, the switch will not be fully insulated and electrons will shunt current across the switch gap, preventing higher load voltage. Thus this analysis shows what level of voltage and power multiplication can be reasonably expected on various generators using a PEOS which can be made to conduct the full machine current before opening quickly.

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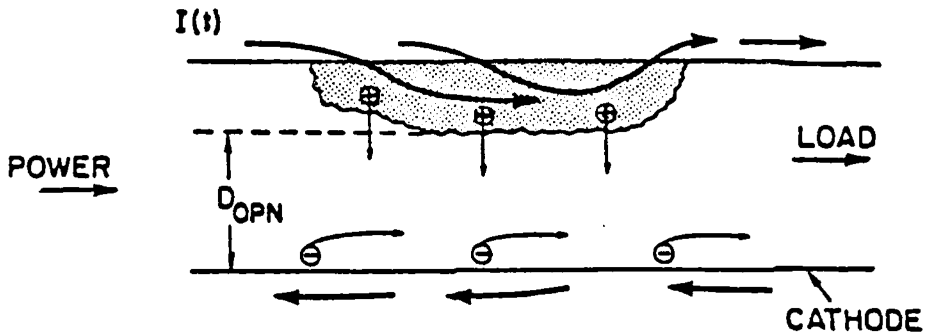
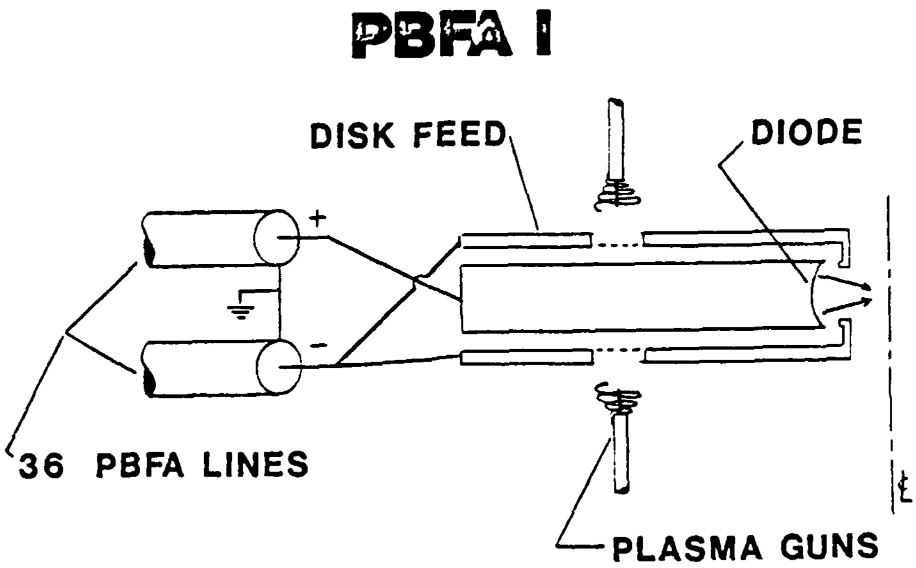
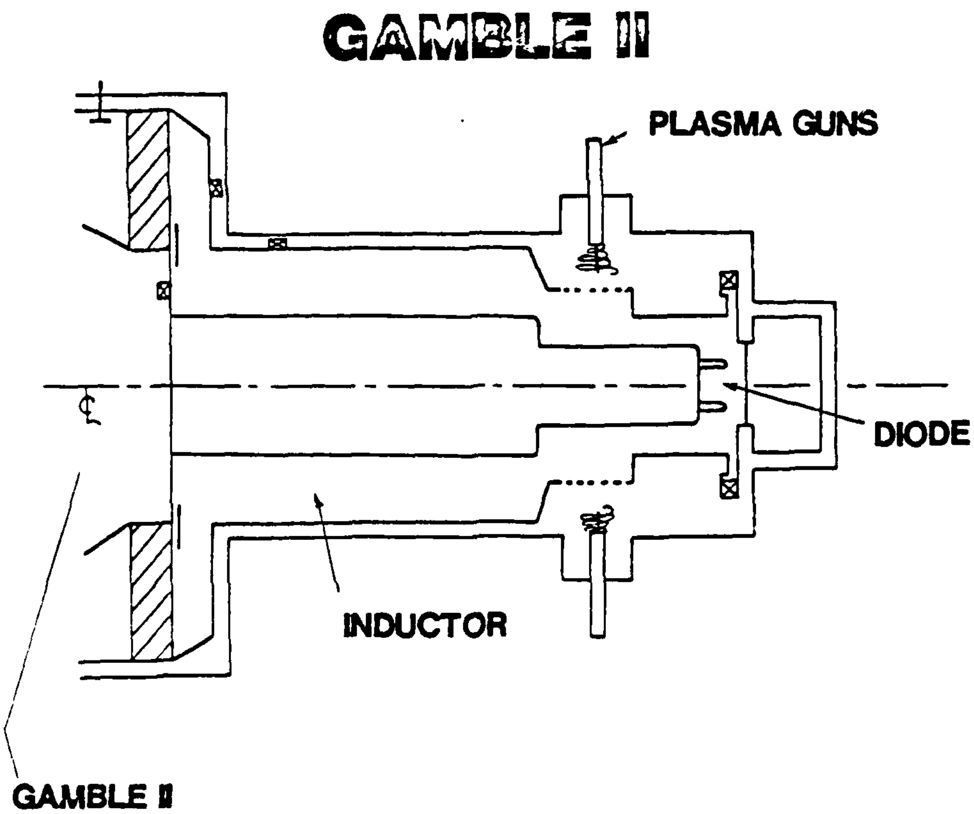


Fig. 1. Schematic of PEOS in opened state.



(a)



(b)

Fig. 2. Schematic of (a) PBFA I triplate geometry and (b) Gamble II cylindrical geometry with plasma gun positions indicating loaction of PEOS.

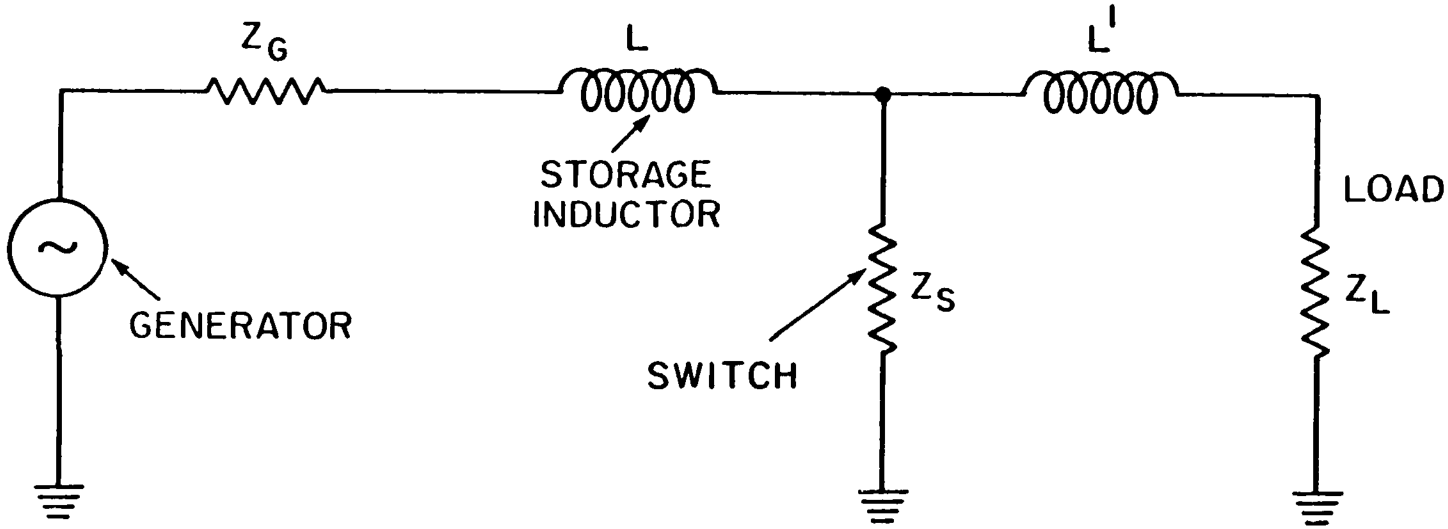


Fig. 3. Simplified equivalent circuit for generator with PEOS system and load.

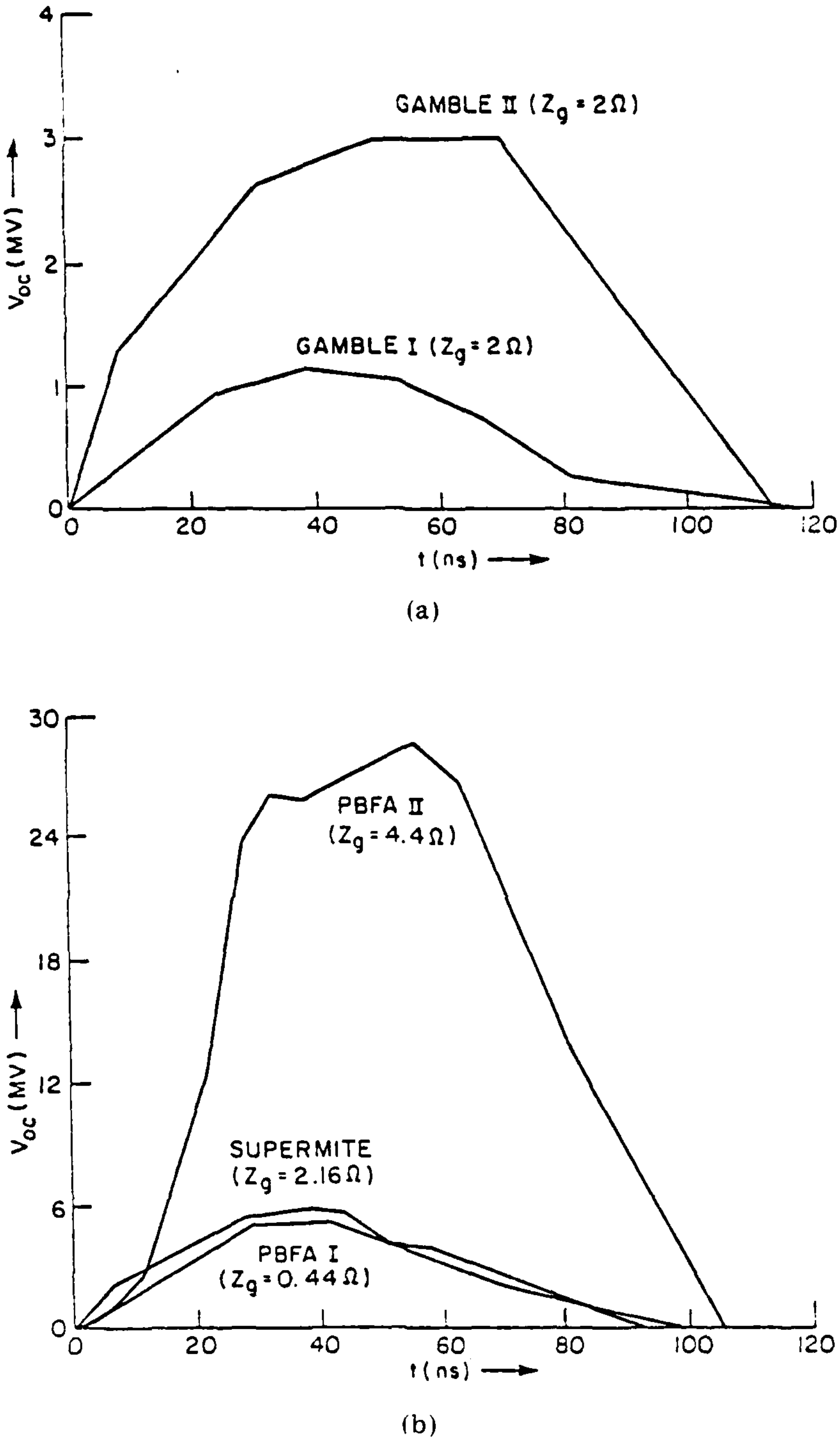


Fig. 4. Open circuit voltage waveform and generator impedance for (a) Gamble I and Gamble II and (b) PBFAI, PBFA II and Supermite.

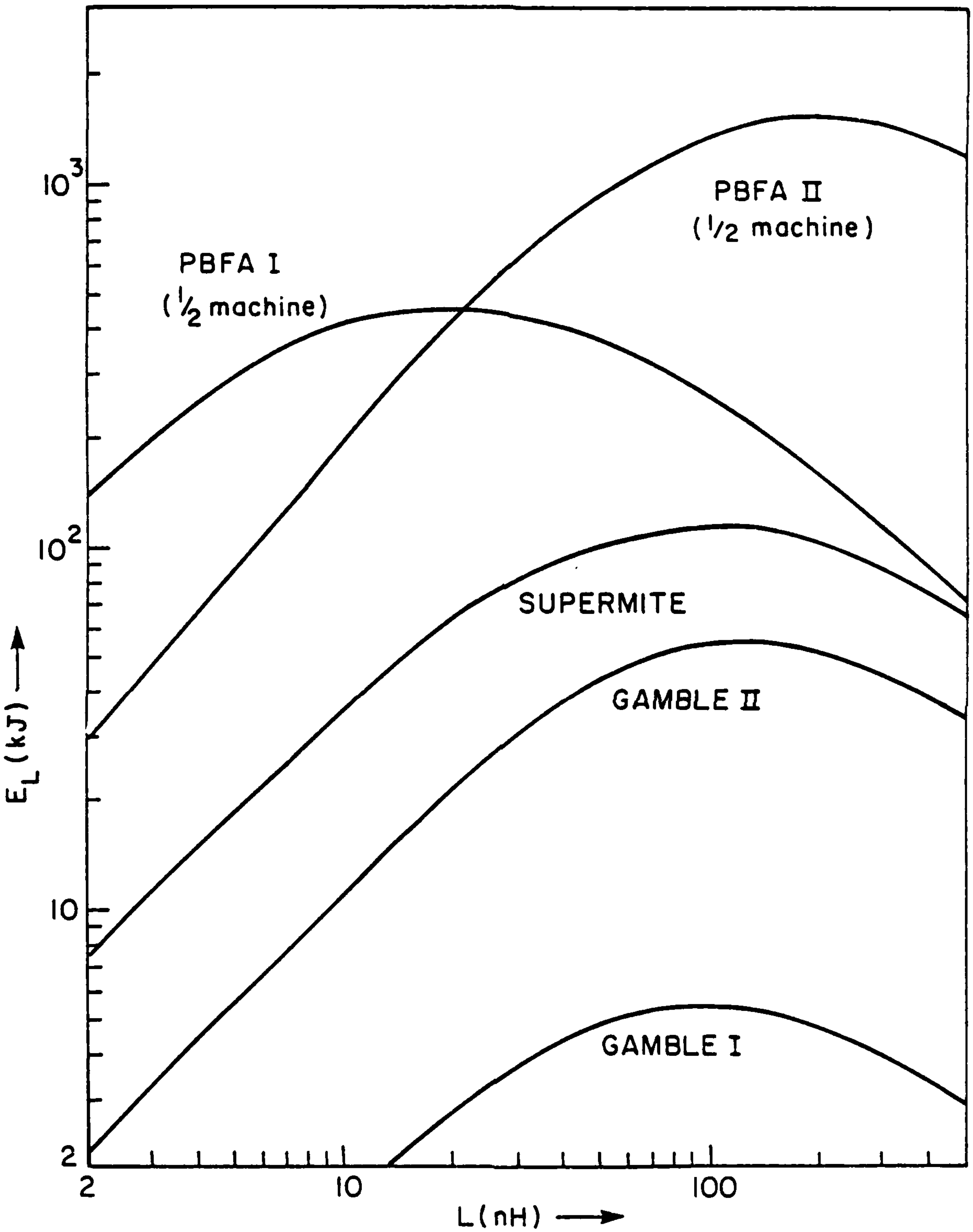


Fig. 5. Inductively stored energy as a function of inductance for various generators.

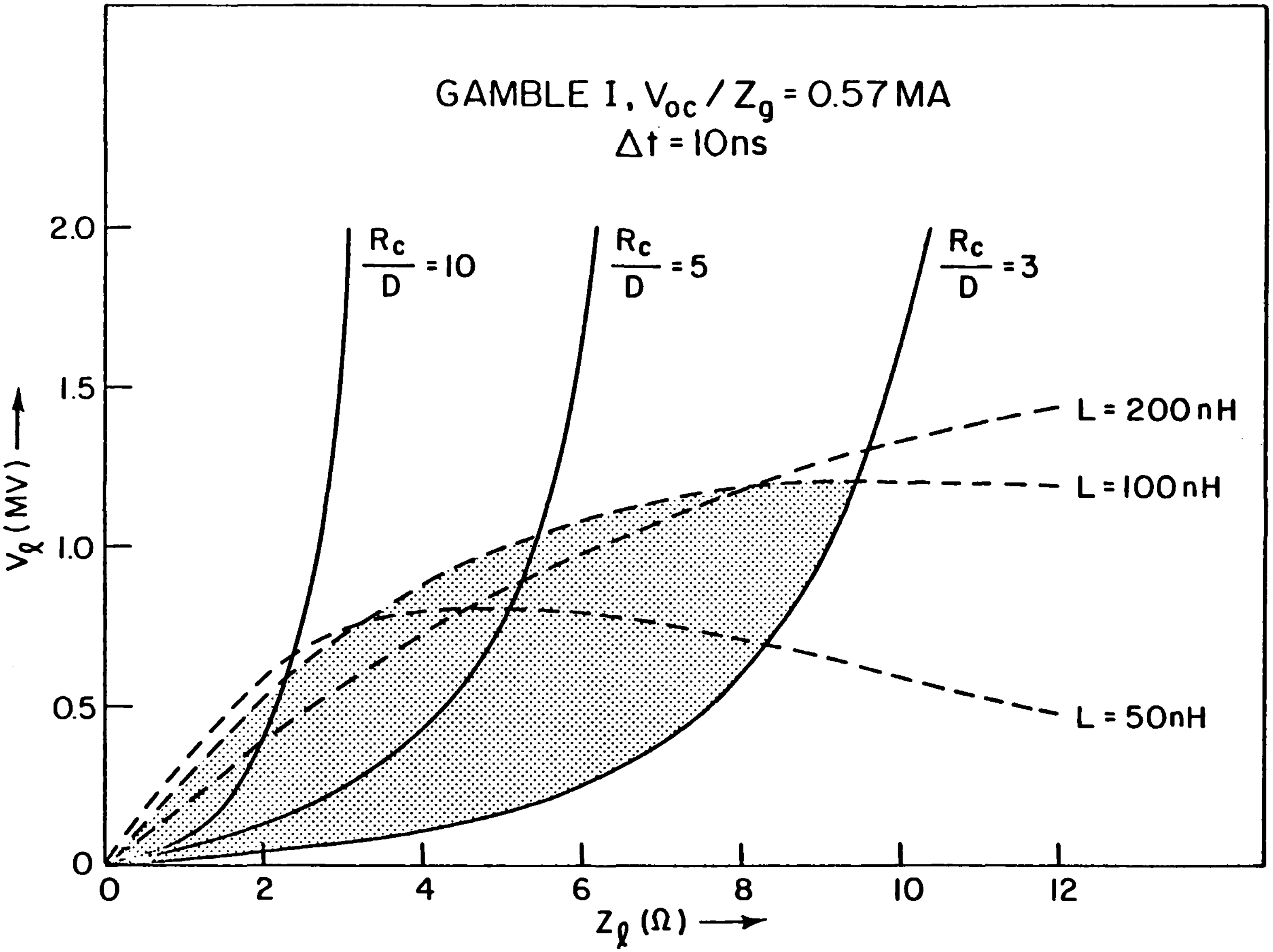


Fig. 6. Operational window for Gamble I and Δt = 10 ns.

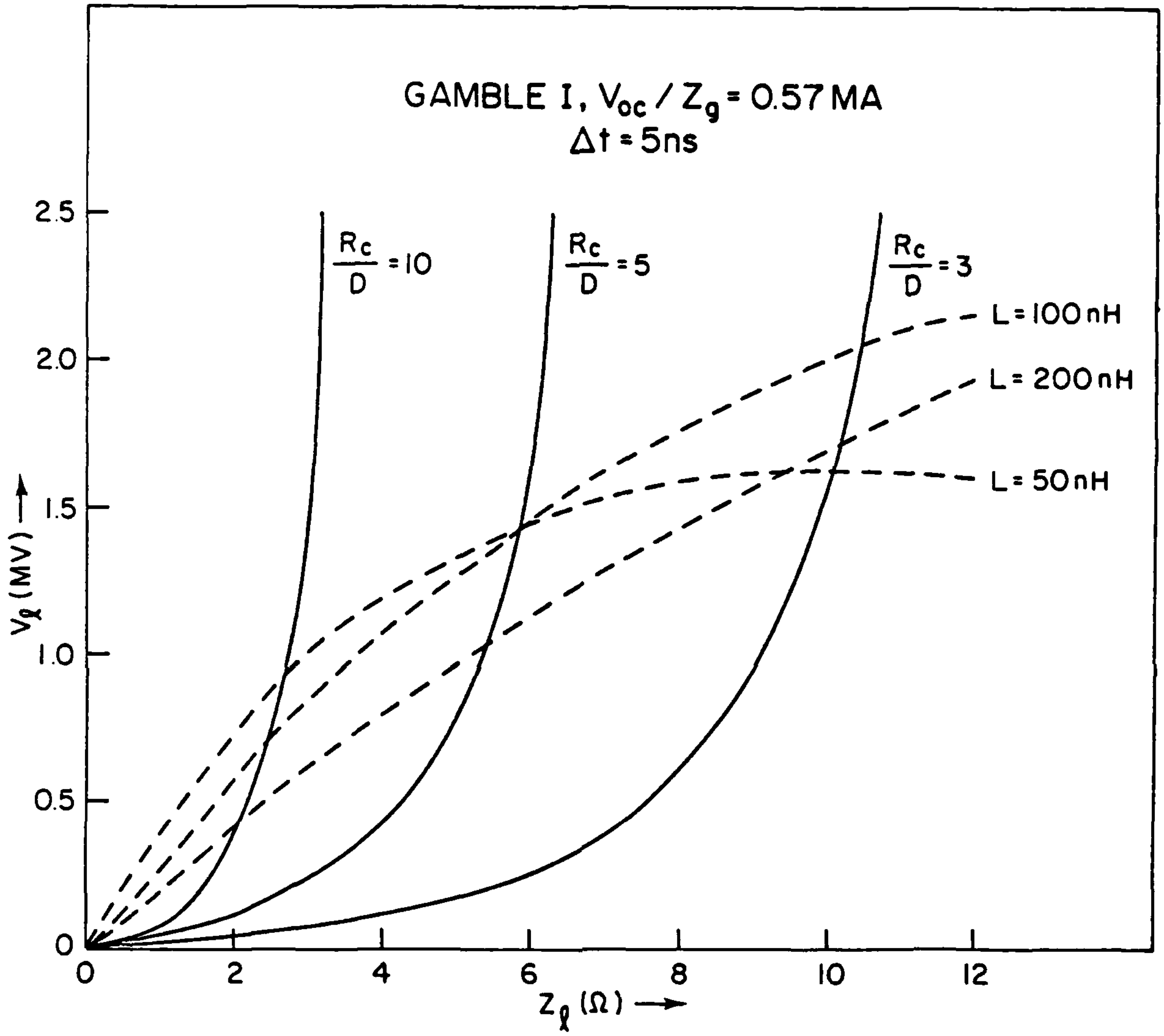


Fig. 7. Operational window for Gamble I with Δt = 5 ns.

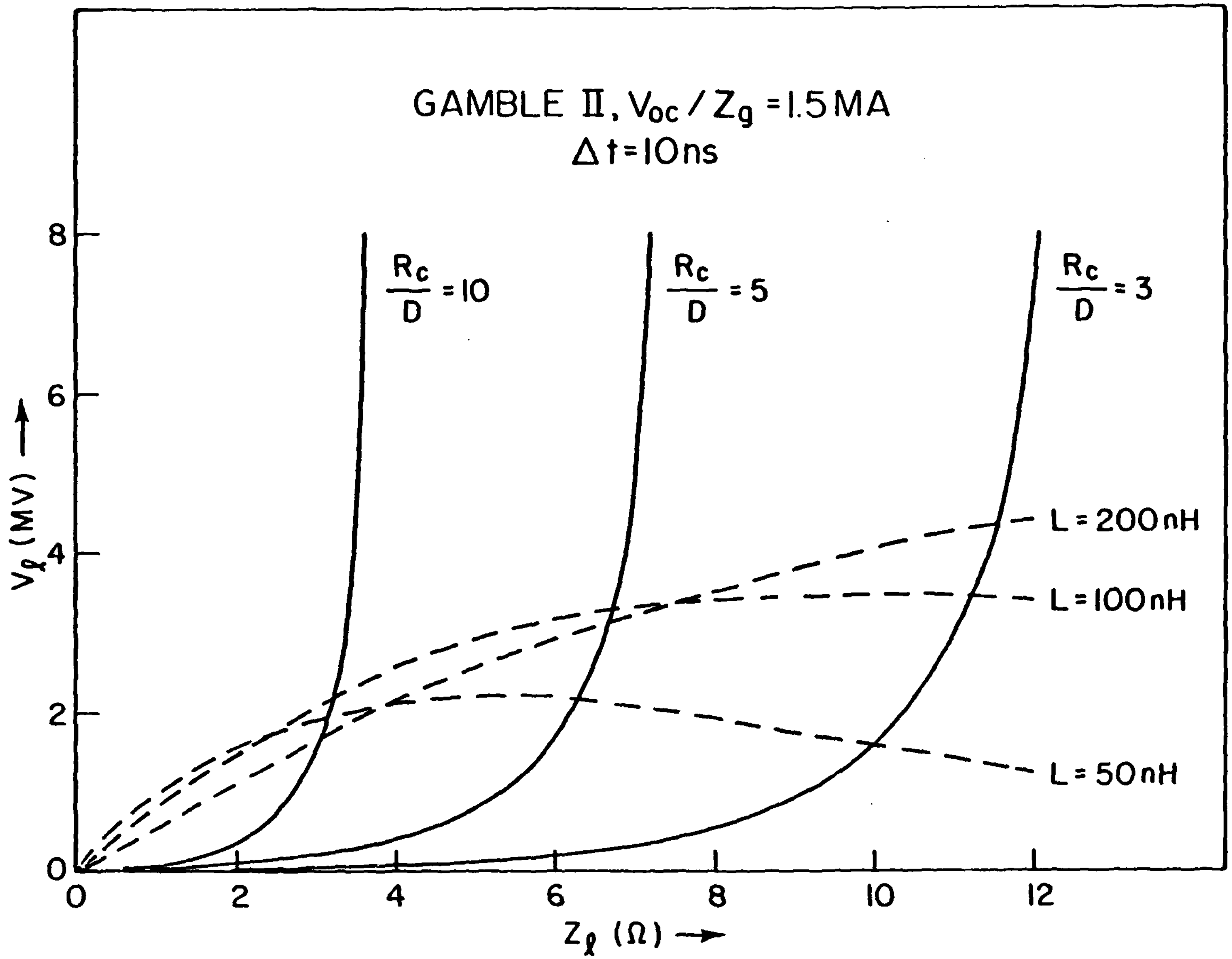


Fig. 8. Operational window for Gamble II with Δt = 10 ns.

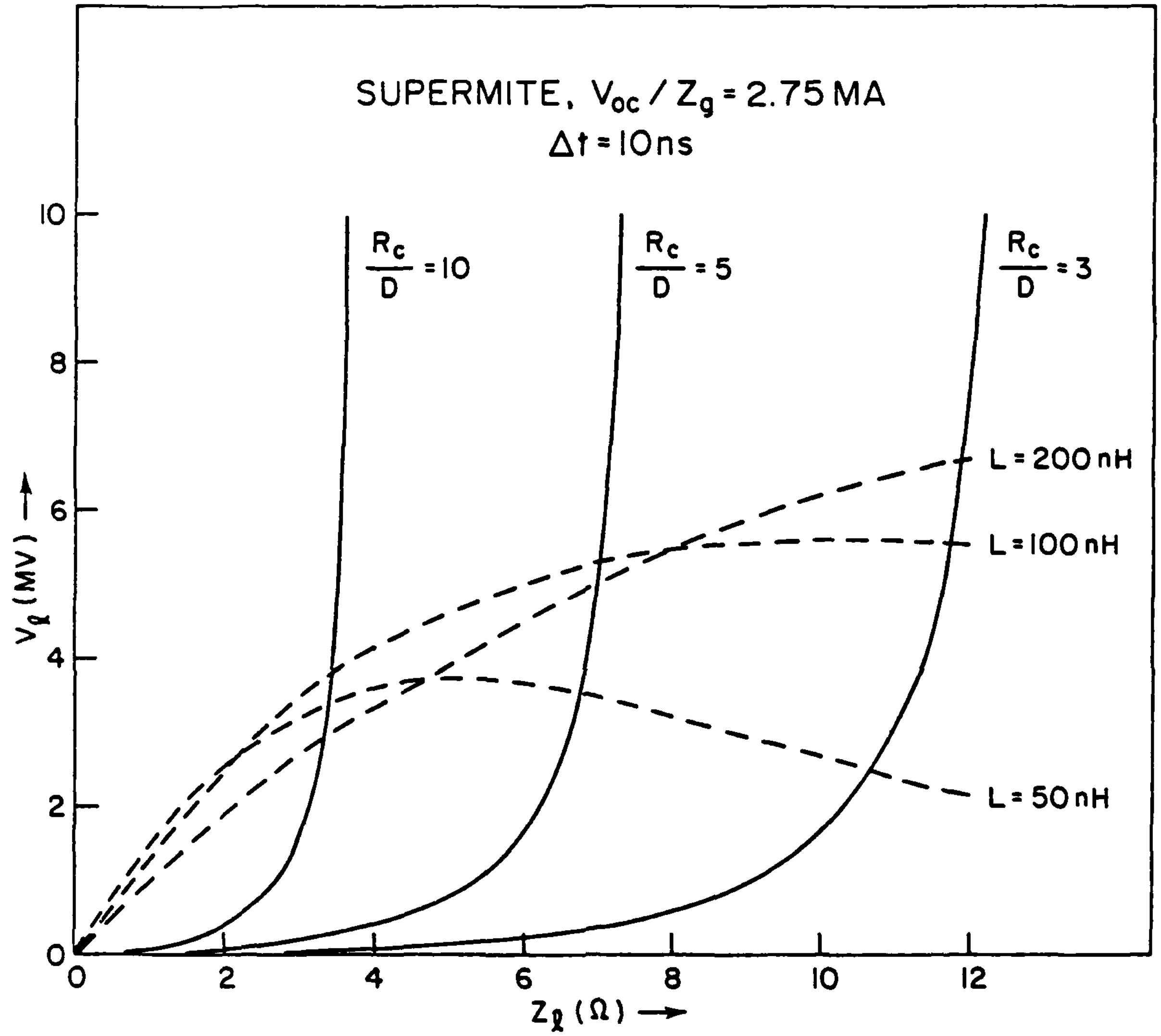


Fig. 9. Operational window for Supermite with Δt = 10 ns.

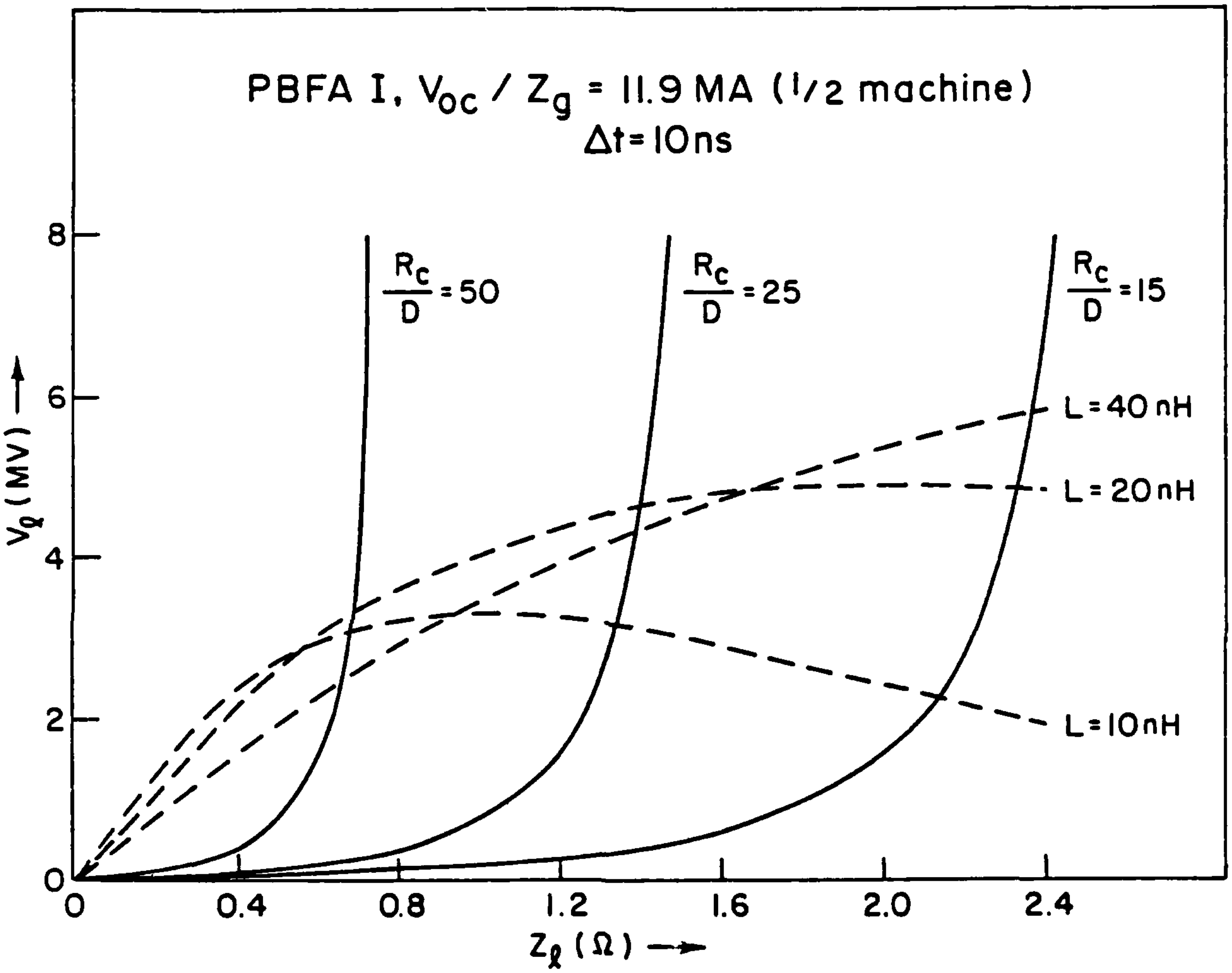


Fig. 10. Operational window for PBFA I with Δt = 10 ns.

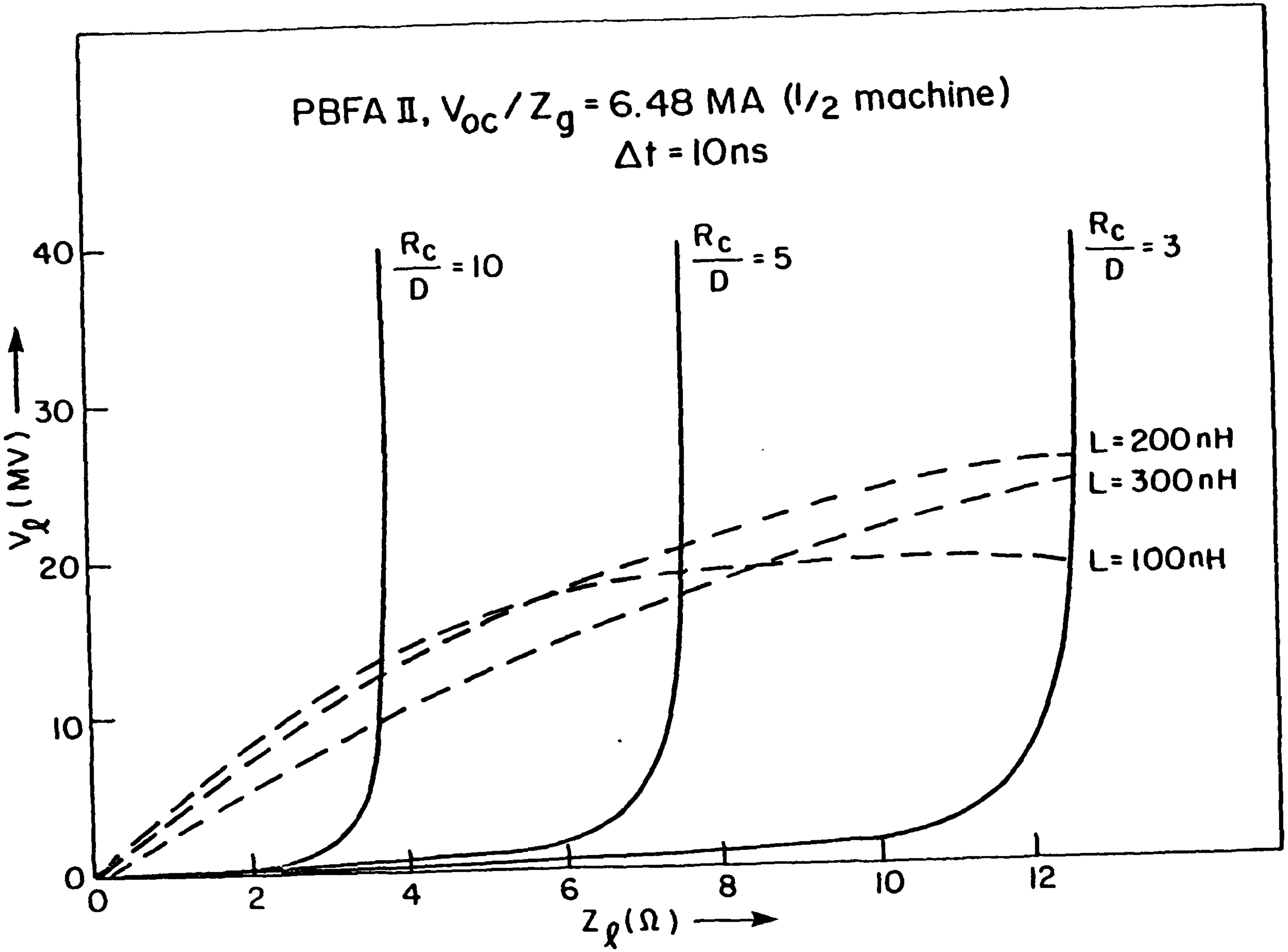


Fig. 11. Operational window for PBFA II with Δt = 10 ns.

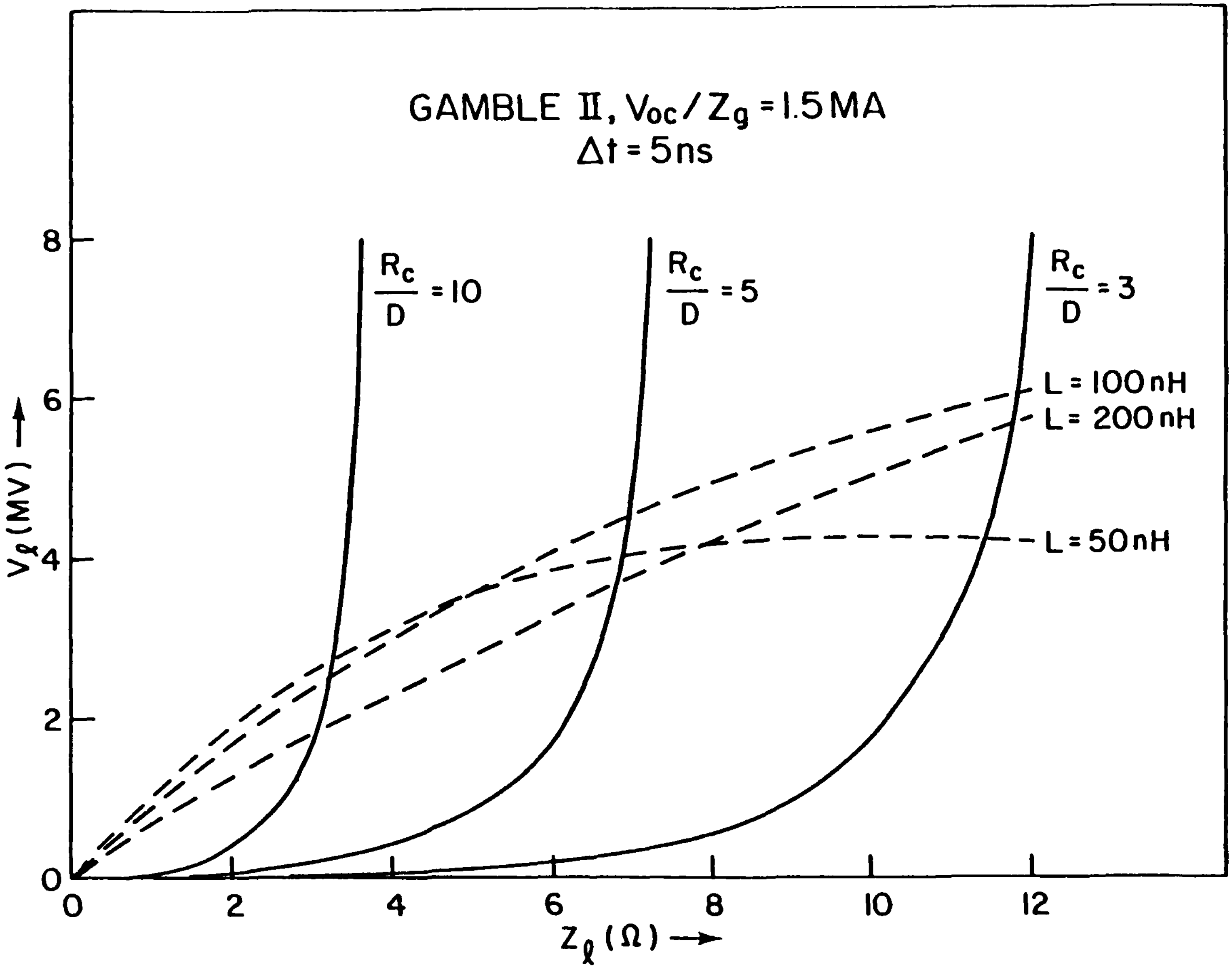


Fig. 12. Operational window for Gamble II with Δt = 5 ns.

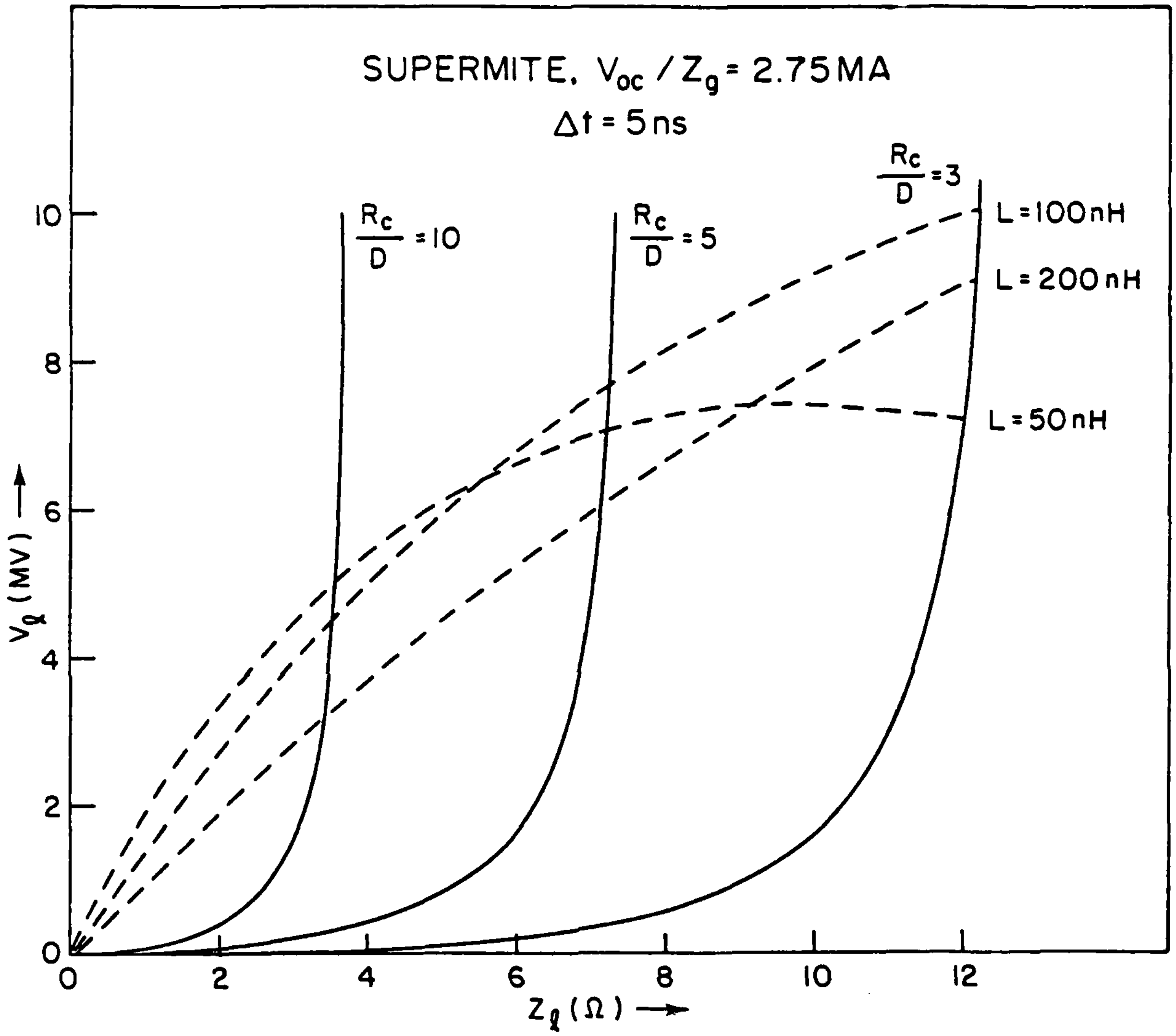


Fig. 13. Operational window for Supermite with Δt = 5 ns.

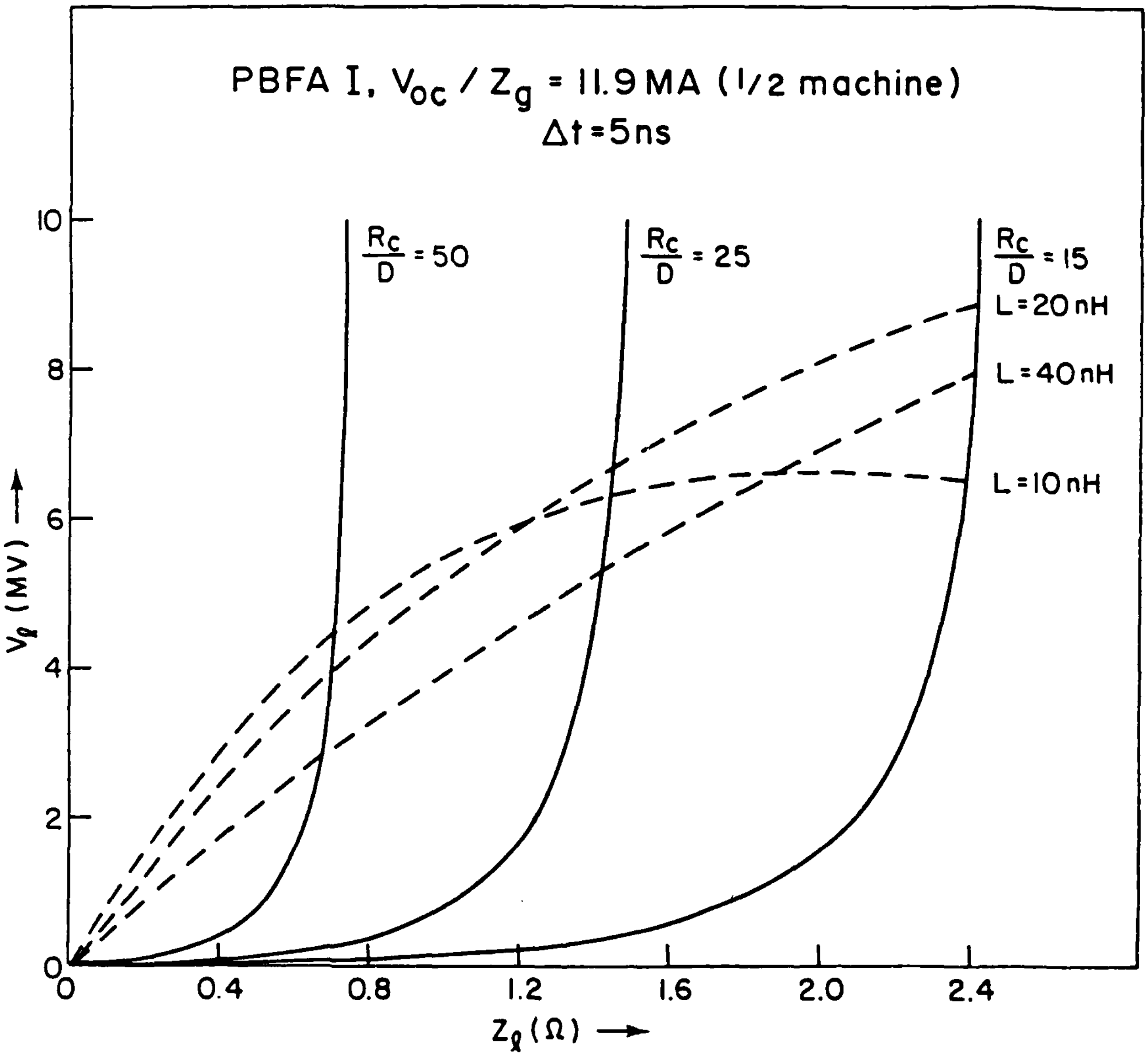


Fig. 14. Operational window for PBFA II with Δt = 5 ns.

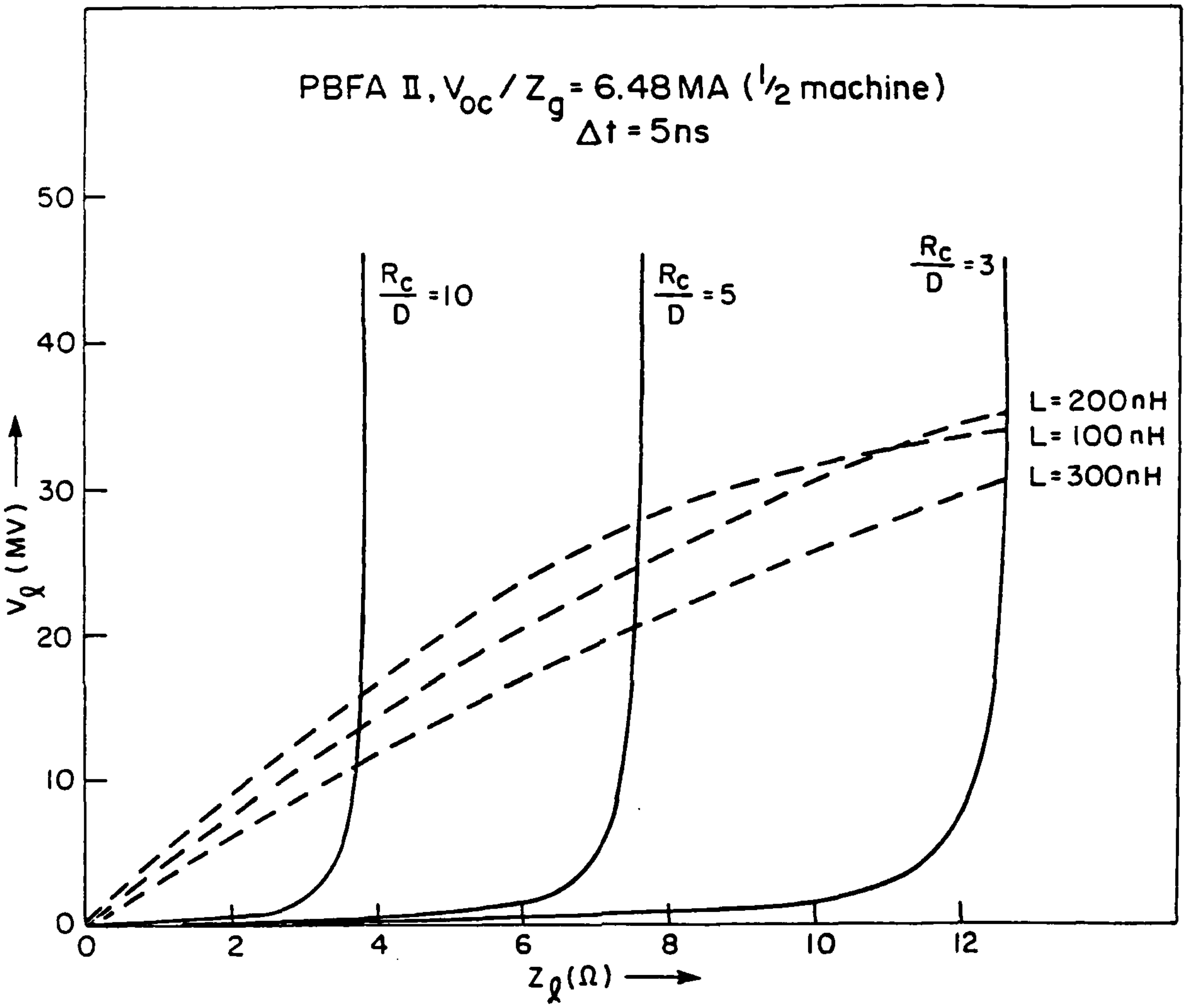


Fig. 15. Operational window for PBFA II with Δt = 5 ns.

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